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The affordance of gap crossing in toddlers

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Abstract

The aim of the present study was to determine factors that significantly predict gap crossing in toddlers. Forward multiple regression was performed including anthropomorphic measures, walking skill parameters, walking experience, and age as independent variables and gap crossing threshold as the dependent variable. Seventy-six percent of the variance in gap crossing thresholds was explained by the amount of walking experience. No other variable significantly contributed to the amount of explained variance. Thus, walking experience is the most significant predictor of the affordance of gap crossing in toddlers. The fact that walking experience, but not age, significantly predicts gap crossing thresholds, strongly opposes a strictly maturational point of view of motor development and favours the ecological point of view, in which appropriate coupling of action and perception arises through exploration of the environment.

Keywords: Gap crossing; Walking experience; Perception-action coupling

1. Introduction

In 1979 Gibson formulated the concept of affordances: 'the *affordances* of the environment are what it *offers* the animal'. Affordances are invariant properties of the environment taken with reference to the individual. This implies that an affordance is bidirectional, involving both the environment and

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individual. For example, affordances for action are relative to the size of the individual (Gibson, 1979, chap. 8). Warren (1984, 1988) showed that there was an invariant that specifies if a stair affords to being climbed, which depends on both the environment, the riser height, and on the individual, the leg length. However, action does not exclusively have to be scaled in anthropomorphic measures. More extensive research by Konczak, Meeuwsen, and Cress (1992) on stair climbing examined in addition to leg length and a body-scaled ratio, the maximum amount of hip flexion and the maximum extension strength. For young adults, the maximum amount of hip flexion and the maximum extension strength was shown in a stepwise regression to explain more of the variance than leg length. However, for older adults, leg length and the body-scaled ratio explained the largest amount of variance.

In young children, it has been shown that anthropomorphic measurements are not the best predictors of action capabilities and affordances (Adolph, 1995; Adolph, Eppler, & Gibson, 1993; Kingsnorth & Schmuckler, 2000; Schmuckler, 1996). With respect to walking on slopes in 14-month-old toddlers, Adolph and co-workers showed that walking skill was the best predictor for ascent and descent boundaries. In addition, research on the affordance of barrier crossing showed that barrier crossing thresholds in 1- to $2\frac{1}{2}$-year-old toddlers were more closely related to differences in experience than to differences in leg length (Schmuckler, 1996). In an attempt to resolve the question of whether walking skill or walking experience was the best predictor of barrier crossing thresholds, Kingsnorth and Schmuckler (2000) disentangled the concepts of walking experience and skill. Walking experience refers to the length of time from onset, while walking skill involves the interplay of a number of contributing variables, such as flexibility, balance and interlimb coordination. Kingsnorth and Schmuckler (2000) found that walking experience was a better predictor for barrier crossing than walking skill. A possible explanation for this result is that the motor demands of barrier crossing are not related to the motor demands of normal walking (Kingsnorth & Schmuckler, 2000). [Note: depends on whether the barrier task was challenging or not and the skill measures that were examined.]

The aim of the present study was to examine factors that significantly predictor gap crossing thresholds in toddlers. Functionally, gap crossing can be seen as a challenging form of normal walking, and seems therefore a plausible setting to further investigate the possible roles of walking skill and walking experience as predictors of action capabilities. The only prior research on gap crossing in children (Leo, Chiu, & Adolph, 2000) focused on 11-month-old infants, who were required to cross a gap using a handrail. At this age, this type of support leads to sideward stepping and is therefore largely dependent on abduction capabilities. This is functionally not comparable with unsupported gap crossing, which largely depends on hip flexion and extension.

Research by Burton (1992) on the affordance of gap crossing in adults showed that judgements of critical crossing boundaries were lower for shorter participants than for taller participants. This effect disappeared when corrected for leg length. Although Burton did not mathematically derive an invariant that specifies if a gap affords being crossed, this finding suggests a body-scaled ratio may predict gap crossing. However, Jiang and Mark (1994) showed that there is a stronger correlation between eye height and judgements of maximum crossability in adults, than between leg length and judgements of maximum crossability.

In order to resolve what predicts maximum gap crossing ability in toddlers, possible predictor variables first had to be quantified. To accomplish this a gait analysis based on footprint patterns (e.g., Adolph, 1995; Adolph et al., 1993; Adolph, Vereijken, Byrne, & Ilustre, 1996; Boenig, 1977; Kingsnorth & Schmuckler, 2000; Ledebt, van Wieringen, & Savelsbergh, 2004; Ogg, 1966) was carried out to determine walking skill parameters. In addition, hip flexion, hip extension and range of motion of the hips were measured during walking as additional possible walking skill predictors for gap crossing thresholds. Walking experience was defined as the time that had passed since the start of unsupported walking. Also, in addition to anthropomorphic measures, the age of the child was taken into account as a possible predictor for the maximum distance crossed, because in the traditional, maturational view of motor development (McGraw, 1945) the most important factor is the age of the child. After the gait analysis the actual gap crossing experiment took place. Because visual judgements of affordances have been shown not to be totally accurate in adults (Bingham & Pagano, 1998), the children in our study had to actually cross a gap.

2. Methods

2.1. Participants

A total of 17 young infants participated in this study. This study was part of a longitudinal study. The Ethical Committee of the Vrije University Hospital, Amsterdam, The Netherlands, approved the protocol. Before the measurements, one of the parents gave his or her informed consent regarding the participation of his or her child. The infants ranged in age from 25 to 38 months. For 2 of the 17 children, no kinematic data was recorded due to refusal by the infant to wear goniometers.

2.2. Experimental set-up for gait analysis

The infants had to walk five times from one end of a small platform to the other end. The platform was 4 m long, had a width of 1 m, and was 14 cm high. All trials were recorded by a video camera. The participants walked on a sheet of paper that was fixed to the platform. Ink-covered pads were attached under the toes and heels of the soles of the child's shoes, resulting in footprints on the paper as the infant walked over the platform. The co-ordinates of the toe and heel prints on the paper were then scanned on a graphic table (Drawingboard III, Calcomp, Anaheim, USA) and digitised. For an extensive description of the above procedure see Ledebt et al. (2004). Goniometers (SG110, Biometrics, Gwent, UK) were attached to the infant to measure hip angles in the sagittal plane. A reference measurement was made to determine the angles at which the goniometers were placed when the participant stood straight. Video and goniometer data collection was synchronised by means of a pulse that was given when the child started to walk. In this way, the signals of the goniometers could be related to actual walking. Before the measurements started, infants performed a few practice trials to make sure that the child was comfortable with the procedure.

2.3. Experimental set-up for gap crossing

After the gait trials, the gap crossing experiment was conducted. In this experiment the participant stood in front of a 2 m × 1 m long platform and had to walk to the end of the platform and then step over a gap to another 1 m × 1 m platform (see Fig. 1). The infant was required to step straight ahead across the gap. The depth of the gap was 14 cm.

Gap span (distance) was regulated on basis of a psychophysical staircase procedure (Adolph, 1997, 2000). This procedure enabled the identification of a threshold using a minimal number of trials. The distance in the first trial was very low (base-line = 6 cm), distance was then increased with fixed steps of

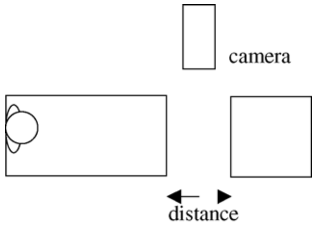

Fig. 1. Top view gap crossing set-up.

6 cm until the participant failed (stepped into the gap or lost balance while crossing the gap) or refused to cross. This step was then repeated. If the infant failed or refused on the second trial at that distance, the base-line condition was repeated for motivation purposes. The next distance was 4 cm less than the last failed distance. This process continued until a participant was successful at least 2 out of 3 trials at a certain distance, and was unsuccessful at least 2 out of 3 trials at the next largest distance (Adolph, 1997). This psychophysical staircase procedure enabled gap boundaries to be determined within 2 cm.

2.4. Analysis

2.4.1. The anthropomorphic variables

For each participant the total height, the eye height and the leg length were measured by the same experimenter. Leg length was defined as the distance from the spina iliaca anterior superior to the medial malleolus.

2.4.2. Walking skill variables

Walking skill parameters were obtained from the footprint patterns and included: step length, step width, foot rotation and foot rotation asymmetry. Step length was defined as the distance from one heel print to the next (e.g., step length on the right side is the result of the right heel co-ordinate minus the previous left heel co-ordinate). Step width was defined as the distance between the heel co-ordinate of one foot and the heel co-ordinate of the next foot. The rotation of the foot was defined as the angle between the line connecting the heel in that position and toe print in that position and the line connecting the heel print and the next heel print of the foot in question. A positive value of the angle indicated an out-toeing position and a negative value an in-toeing position of the foot. After each step the asymmetry of foot rotation was defined as the absolute value of difference between the rotations of the supporting foot and the landing foot. It has to be noticed that the same value can be obtained with different left–right rotations.

2.4.3. Kinematic walking skill variables

Walking skill variables obtained from the kinematic data included mean hip flexion, mean hip extension and mean hip range of motion (ROM_{hips}). Data from the goniometers was first filtered with a fourth order low pass Butterworth filter with a cut-off frequency of 10 Hz. Flexion was defined as the maximum angle per step measured by the goniometer minus the reference flexion angle. Extension was defined as the minimum angle per step measured by the goniometer minus the reference extension angle. Range of motion for each leg was defined as the maximum angle minus the minimum angle per step. Mean flexion, mean extension and mean ROM_{hips} of each leg was then calculated.

Table 1
Demographic data and maximum gap crossing distance

Participant	Gender	Age (months)	Walking experience (months)	Height (cm)	Eye height (cm)	Leg length right (cm)	Leg length left (cm)	Maximum gap distance (cm)
A	♀	25	12	83.5	75.0	37.0	37.0	30
B	♀	25	11	88.0	79.0	40.0	40.0	36
C	♀	26	9	84.0	74.0	35.0	35.0	24
D	♂	28	13	93.0	83.0	41.0	41.0	30
E	♀	28	17	90.0	79.0	39.0	39.0	42
F	♂	29	15	98.0	88.0	45.0	45.0	36
G	♂	29	15	96.0	88.0	46.0	46.0	32
H	♂	29	18	89.5	81.0	40.0	40.0	44
J	♀	30	17	88.0	78.0	37.0	37.0	38
K	♂	31	14	94.0	83.0	44.0	43.5	36
L	♂	31	14	91.0	80.0	40.0	40.0	24
M	♂	33	22	95.0	86.0	40.0	40.0	48
N	♀	33	19	91.0	81.0	40.0	40.5	38
O	♂	35	19	95.0	85.0	40.0	40.0	42
P	♂	36	19	98.5	88.5	44.0	44.0	48
Q	♂	36	21	97.0	87.0	44.0	43.5	48
R	♀	38	27	93.5	84.0	41.0	41.0	48

2.4.4. Walking experience

Walking experience was calculated by subtracting the age at the start of unsupported walking from the current age (in months). Start of unsupported walking was defined as the age at which the child could make at least five successive steps without support and without losing balance. This information was provided by the parents.

The dependent variable in the gap crossing experiment was the maximum distance crossed (in cm).

2.5. Statistical analysis

Statistical analysis was performed using SPSS 10.0. Forward multiple regression was performed with age, walking experience, leg length (right/left), eye height, total height, step length (right/left), step width, foot rotation (right/left), foot rotation asymmetry, hip flexion (right/left), hip extension (right/left) and ROM_{hips} (right/left) as independent variables and maximum distance crossed as the dependent variable.

3. Results

Individual demographics and gap crossing performance can be found in Table 1. Individual results for the walking skill parameters can be found in Table 2. Forward multiple regression including all infants showed that walking experience in months was the sole significant predictor for the maximum distance crossed ($R^2 = 0.76$, $P < 0.001$; see Fig. 2). Table 3 shows the partial correlation (the influence of walking experience is partialed out) and amount of explained variance of the residual variables with the maximum

Table 2
Individual walking skill parameters

Participant	Step length left (cm)	Step length right (cm)	Step width (cm)	Foot rotation left (°)	Foot rotation right (°)	Foot rotation asymmetry (°)	Flexion right leg (°)	Ext. right leg (°)	Flexion left leg (°)	Ext. left leg (°)	ROM right (°)	ROM left (°)
A	26.64	27.51	8.77	12.0	15.5	7.0	21.4	−15.0	26.0	−9.9	36.6	36.1
B	18.22	20.55	10.77	−1.6	9.9	12.0	28.7	1.4	23.2	−0.2	27.5	23.6
C	22.87	23.31	11.80	−2.6	−10.4	8.5	37.6	2.2	32.4	−0.8	35.3	33.4
D	33.56	35.61	11.88	−3.7	3.0	12.7	21.9	−2.4	31.8	−2.6	24.7	33.8
E	36.83	32.80	11.02	−2.4	−4.5	8.4	35.1	−3.6	40.4	2.5	38.9	38.3
F	26.36	28.67	7.66	−0.7	−1.7	5.8	31.2	−4.3	32.5	−3.2	35.3	35.8
G	29.15	30.85	9.00	6.2	3.9	7.1	23.3	−8.0	20.1	−16.7	31.5	36.5
H	34.64	35.33	6.00	13.1	10.4	8.5	–	–	–	–	–	–
J	30.60	31.23	7.79	−0.8	−5.6	10.6	23.0	−10.2	22.9	−11.7	33.5	34.1
K	28.58	27.63	9.47	5.3	−3.3	14.1	34.4	3.2	27.7	−2.4	31.3	30.1
L	34.30	33.34	6.36	−11.4	−11.4	8.7	24.0	−2.6	30.5	−5.5	26.3	36.5
M	33.59	33.17	10.52	−7.5	−3.5	8.2	29.1	−4.9	34.5	−2.3	34.0	37.2
N	31.36	27.09	11.15	−14.7	−2.3	12.8	30.8	−6.6	33.6	2.3	37.6	31.3
O	34.78	40.19	10.95	4.1	−2.0	9.7	–	–	–	–	–	–
P	35.34	35.39	10.54	−5.8	−0.2	8.2	21.1	−7.5	29.6	−2.3	28.4	31.5
Q	29.58	25.06	11.66	−11.7	5.6	21.6	31.2	3.6	31.3	3.0	27.3	28.3
R	33.13	33.38	7.81	11.1	8.0	6.5	34.9	−1.9	32.6	−1.5	36.5	34.1

Table 3
Partial correlation and amount of explained variance of the residual variables with the maximum distance crossed

Variable	Partial correlation	*P* value	R^2
Step width	0.410	0.075	0.17
Height	0.310	0.302	0.10
Eye height	0.291	0.335	0.08
ROM_{hips} left	−0.272	0.369	0.07
Hip extension left	0.265	0.382	0.07
Foot rotation asymmetry	0.241	0.428	0.06
Leg length right	0.218	0.475	0.05
Leg length left	0.194	0.525	0.04
Hip flexion left	0.144	0.639	0.02
Foot rotation right	0.101	0.743	0.01
Step length right	−0.091	0.767	0.01
Foot rotation left	−0.045	0.883	0.00
Hip flexion right	0.045	0.884	0.00
ROM_{hips} right	0.043	0.888	0.00
Age	0.027	0.930	0.00
Hip extension right	0.023	0.942	0.00
Step length left	0.014	0.964	0.00

The influence of walking experience is partialed out.

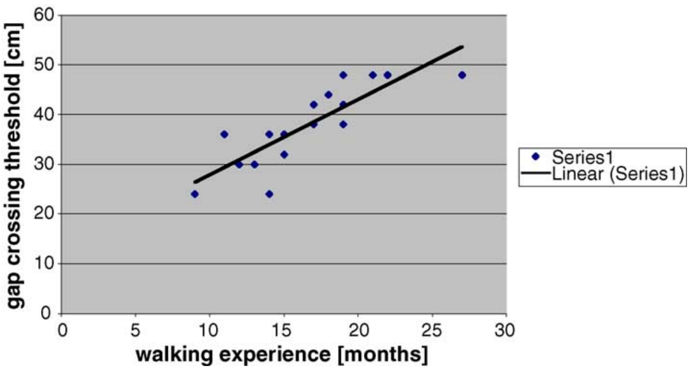

Fig. 2. Linear regression of walking experience and gap crossing threshold ($P < 0.001$, $R^2 = 0.76$).

distance crossed. As can be seen in the table, none of the skill variables significantly predicted gap crossing when walking experience was partialed out.

4. Discussion

In the present study, possible predictors of gap crossing thresholds in toddlers were examined. Anthropomorphic measures, gait parameters, walking experience and age were studied as potential predictor variables. Based on a conceptually related study by Kingsnorth and Schmuckler (2000) on the affordance of barrier crossing, hip flexion, hip extension and range of motion of the hips during walking were also taken into account as gait parameters. However, walking experience proved to be the sole significant predictor of gap crossing thresholds in young children. This clearly is in accordance with the results from the study by Kingsnorth and Schmuckler (2000) which showed that walking experience was the best predictor of barrier crossing thresholds in toddlers.

One of the two explanations Kingsnorth and Schmuckler (2000) discussed for the lack of predictive value of gait parameters was that the motor demands of barrier crossing apparently are not strongly related to the motor demands of normal walking. The current findings extend this explanation to gap crossing, namely that the present gait parameters indexing walking skill does not have predictive value in a gap-crossing task, one that is similar to normal gait. A second possible explanation discussed by Kingsnorth and Schmuckler was based on a theoretical model by Bril and Brenière (1992) which states that the development of walking consists of two phases. The first phase, which lasts for approximately 6 months, involves stabilisation of the trunk (Ledebt & Bril, 2000), while the second phase is regarded as fine tuning of gait parameters that lasts till the age of 7–8 years (Bril & Brenière, 1993; Cheron, Bengoetxea, Bouillot, Lacquaniti, & Dan, 2001). During the first phase, gait parameters are considered to have predictive value for motor performance, as has been shown for walking up and down slopes (Adolph, 1995), while during the second phase the amount of experience is considered to be more important. The absence of relation between the gait parameters and the maximum gap in the present study could be due to the fact that all the infants were in the second phase of walking development. During the second phase, the gait parameters as step length and foot rotation have dramatically reduced their rate of development after respectively a rapid increase and rapid decrease that occurred during the first weeks of walking (Ledebt & Bril, 2000; Ledebt et al., 2004). As a consequence the chosen gait parameters might not have been the most appropriate to characterize walking skill during the second period. Brenière and Bril (1998) showed that the vertical acceleration of the centre of mass, indexing balance during the single stance phase, was still going through remarkable changes during the second phase of gait development up to the age of 6 to 7 years. It could be a better way to characterize walking skill in children situated in the second phase of walking development in order to relate it to their ability of gap or obstacle crossing. In fact, crossing a gap or crossing over an obstacle may require a longer single stance phase and, most probably, control over a larger torque on one leg than level walking. Interestingly, it is not age but the walking experience that predicts gap crossing thresholds. This strongly opposes a strictly maturational point of view about motor development and favours the ecological point of view in which interaction with the environment is regarded as being the basis of motor development (Warren, 1990). Through exploration the child learns the relationships between information and his or her own movement (Savelsbergh, Wimmers, Van der Kamp, & Davids, 1999). This interactive process with the environment will lead in time to appropriate coupling of perception and action (Reed, 1982). In this view, the important developmental factor is the amount of experience rather than the age of the child (Adolph, Vereijken, & Shrout, 2003). The present results strongly suggest that infants are still learning to fully use their potential. It is therefore highly possible that anthropomorphic measures (Jiang & Mark, 1994) and flexion and extension capabilities (Konczak et al., 1992) determine gap crossing affordances from the age of 7–8 years onwards.

In conclusion, the affordance of gap crossing in infants was shown to be determined by walking experience, rather than by anthropomorphic measures, walking skill or age. These results are in accordance with the results of an earlier study by Kingsnorth and Schmuckler (2000) on the affordance of barrier crossing. The fact that walking experience but not age significantly predicts gap crossing thresholds, strongly opposes a strictly maturational point of view about motor development and favours a more ecological point of view.

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